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Evolution of the Rhône delta coast since the end of the 19th century / Cinématique du littoral du delta du Rhône depuis la fin du XIXe siècle

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François Sabatier* and Serge Suanez**

Abstract

The evolution of the Rhône delta coast is analysed using digitally processed data obtained from field surveys effected in 1895, aerial photographs taken in 1940, 1950, 1960, 1970, 1980 and 1990, and a DGPS-based survey carried out in 2000. The whole dataset was integrated into a Geographic Information System to determine coastline retreat and advance and to quantify gains and losses of land area at the coastal fringe of the delta. It is shown that sediment input from the Rhône, longshore drift currents and sea defences have had a marked influence on space-time variations of the position of the coastline. These data enable characterisation of the morphosedimentary circulation at the coast, and the identification of a clear pattern of littoral sediment cells.

Key words: Geographic Information System, spit, beach, coastal defences, littoral cell.

Résumé

La cinématique du littoral du delta du Rhône est étudiée par le traitement numérique de relevés de terrains effectués en 1895, de photographies aériennes prises dans les années 1940, 1950, 1960, 1970, 1980, 1990, et d'un relevé au DGPS (Differential Global Positionning System) réalisé en 2000. L'ensemble de ces données a été intégré dans un Système d'Information Géographique pour déterminer des vitesses de recul et d'avancée du trait de côte et pour quantifier les surfaces gagnées ou perdues par la frange littorale. Le rôle des apports sédimentaires rhodaniens, des courants de dérive, et des ouvrages de défense du littoral, dans les variations spatiotemporelles de la position du trait de côte, est mis en évidence. Ces données permettent de dessiner la circulation morphosédimentaire à la côte qui s'organise en cellules de dérive littorale.

Mots clés *: Système d'Information Géographique, flèche littorale, plage, digues, épis, cellules de dérive littorale.*

Version française abrégée

Le delta du Rhône est un delta dominé par la houle dont la forme générale s'articule autour de deux bras : le Grand Rhône à l'est et le Petit Rhône à l'ouest des Saintes-Maries-de-la-Mer. La frange littorale représente environ 90 km de côtes sableuses qui s'étendent de la flèche de la Gracieuse à l'est de l'embouchure du Grand Rhône jusqu'au complexe touristique du Grau-du-Roi à l'ouest de la flèche de l'Espiguette (fig. 1). Alors que les travaux antérieurs sur la cinématique du rivage ne concernent que la partie orientale du delta du Rhône pendant une cinquantaine d'années (Suanez et Simon, 1997 ; Suanez et al.*, 1998), cet article propose une analyse séculaire (entre 1895 et 2000) de l'ensemble du littoral du delta du Rhône.*

Plusieurs étapes, reprises et commentées par M. Provansal et al. *(ce volume), décrivent la construction holocène du delta du Rhône qui commence aux alentours de 7000 BP. Cette histoire montre que l'allure générale du littoral actuel est atteinte au début du XVIII^e^ siècle laissant en mer une morphologie particulière en lobes (Bras de fer et Pégoulier) en face des anciennes embouchures (Vieux Rhône et ancien débouché du Grand Rhône) (fig. 2 et fig. 3). Les données sur la charge solide rhodanienne indiquent une diminution des apports depuis le XIX^e^ siècle : entre 22 et 30 Mt/an au tout début du XX^e^ siècle (Surell, 1847* in *Vernier, 1976 ; Pardé,*

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1925) puis 7,39 à 9,6 Mt/an à la fin de ce même siècle (Antonelli, 2002 ; Pont et al., *2002). Cette diminution s'explique par une moindre fréquence des crues annuelles (Pichard, 1995) en relation avec la fin du Petit Âge Glaciaire. Les effets du climat sont également amplifiés par les mutations de l'occupation du sol dans le bassin versant : la déprise agricole, la reforestation et l'aménagement des cours d'eau, notamment la construction des barrages hydro-électriques à partir des années 1950-1960 qui piègent une grande partie de la charge fluviale grossière. Les houles et les courants qu'elles induisent restent les agents déterminants de la dynamique marine. Les houles proviennent de trois directions principales (fig. 4). La houle de SW est la plus fréquente (30 % du total du régime) mais elle est peu énergétique. Les houles de SSE et ESE représentent respectivement 16 % et 11 % du régime total annuel ; elles sont très énergétiques et associées à la cyclogenèse méditerranéenne qui se manifeste principalement aux périodes d'équinoxe. Aujourd'hui, plus de 80 % de la frange littorale est équipée de structures de protection côtière (Suanez et Sabatier, 1999). La flèche de la Gracieuse est renforcée par une dune artificielle depuis 1988 tandis que l'avancée des crochons est contrôlée par l'échouage de barrages qui jouent le rôle d'épis (photos 1 et 2). Le littoral de Faraman, des Saintes-Maries-de-la-Mer et de Petite Camargue est équipé de plusieurs batteries d'épis, de nombreuses digues et de quelques brises-lames depuis le milieu des années 1980 (photos 3, 4 et 5). Au bout de la flèche de l'Espiguette, une digue a été édifiée en 1968 pour bloquer le transit littoral et protéger la marina de Port Camargue de l'ensablement (photo 6).*

Les données utilisées dans cet article pour étudier la cinématique du littoral du delta du Rhône reposent : 1) sur des levés de la position du rivage qui ont été effectués par les ingénieurs de l'EPSHOM en 1895 ; 2) sur une collection de photographies aériennes couvrant la période allant de 1944 à 1998 avec une périodicité de 5 à 10 ans (tab. 1) ; enfin, 3) sur un levé effectué en 2000 au moyen d'un GPS différentiel. Reposant sur des techniques modernes de traitement numérique d'images et d'analyse par Système d'Information Géographique (SIG), ce travail fournit des données nouvelles et exhaustives sur les variations du trait de côte (fig. 5 à 10) et sur les surfaces gagnées ou perdues par la frange littorale (fig. 11 et fig. 12).

Les variations du trait de côte montrent que, sur l'ensemble de la période, les valeurs les plus importantes sont enregistrées à proximité des embouchures du Grand Rhône et du Petit Rhône, respectivement +2500 m et -1000 m ainsi que sur les flèches sableuses de la Gracieuse (+2600 m), de Beauduc (+1500 m) et de l'Espiguette (+1500 m) (fig. 5, 6, 8, et 10). Les littoraux de Faraman, des Saintes-Maries-de-la-Mer et de la Petite Camargue qui représentent 70 % du linéaire côtier sont soumis à l'érosion et enregistrent respectivement un recul supérieur à 250 et 500 m depuis 1895 (fig. 7 et 9). L'évolution séculaire nette entre les surfaces gagnées et perdues par la frange littorale est excédentaire de 2,38 km², mais dans le détail, trois périodes se distinguent (fig. 11). Entre 1895 et 1944, le littoral camarguais enregistre un gain de 3,87 km², entre 1944 et 1987-89-90 une perte de 1,70 km² et enfin un léger gain de 0,21 km² entre 1987-90 et 1998-2000. La répartition spatiale de l'évolution de la frange littorale divise le littoral du delta du Rhône en deux secteurs (fig. 12) : le premier, de la flèche de la Gracieuse à l'est du Grau de la Dent où les variations du trait de côte sont chaotiques et ne montrent pas de tendance évidente sur la durée de l'étude ; le second, situé à l'ouest du Grau de la Dent jusqu'à l'Espiguette, où les secteurs en recul et en avancée se distinguent clairement.

Les résultats de la cinématique du rivage mettent d'abord en évidence le rôle des structures de protection côtière qui limitent le recul du rivage depuis les années 1980 et 1990. Cependant, l'évolution sous-marine demeure mal connue et l'on peut s'attendre à une déstabilisation des ouvrages à plus long terme (Paskoff, 1998 ; Sabatier et Provansal, 2002). Ensuite, notre analyse souligne les liens entre l'évolution de la frange littorale et les apports sédimentaires du fleuve à la mer. Pendant les périodes de forts débits (entre 1895 et 1944), le littoral avance tandis qu'il recule ensuite (entre 1944 et 1987-90) en relation avec une diminution drastique des apports rhodaniens. Cette dernière s'explique par la déprise agricole et avec elle, la re-végétalisation du bassin versant rhodanien (Bravard, 1989 ; Warner, 2000). De plus, cette période enregistre les conséquences de la fin du Petit Âge Glaciaire auxquelles s'ajoutent, à partir des années 1950-1960, les effets de la construction des barrages hydro-électriques qui piègent une grande partie des débits solides fluviaux (Klingeman et al., *1994 ; IRS, 2001). Enfin, la cinématique du trait de côte est interprétée selon le concept de la cellule de la dérive littorale qui associe un secteur d'accumulation alimenté en sables par un secteur en cours d'érosion sous l'effet de la circulation modale des courants de dérive (Komar, 1998) (fig. 13). Nous distinguons quatre cellules littorales dont la plus originale (CEL 3) se trouve dans la partie centrale du delta où elle est alimentée à l'est et à l'ouest par deux secteurs en voie d'érosion (fig. 13). Le golfe et la flèche de Beauduc jouent aujourd'hui le rôle de "réservoir" pour le littoral du delta du Rhône tout comme le prodelta de Roustan qui est nourri par les apports rhodaniens. Le démantèlement des sous-deltas fossiles de Pégoulier et du Bras de Fer participe également à la dynamique morpho-sédimentaire actuelle en alimentant en sables le littoral.*

La connaissance de la cinématique du trait de côte, depuis 105 ans, effectuée au moyen d'un SIG permet de proposer des cartes utiles aux aménageurs de l'espace littoral.

Introduction

The evolution of the Rhône delta coast (fig. 1) has been the subject of many studies, the earliest of which date back to the 1950s (Duboul-Razavet, 1956; Juniet, 1962; Vernier, 1976; Blanc, 1977). These studies were very localised and based on classical techniques of manual cartography that, nevertheless, threw light on the recent evolution of this deltaic coast. However, such studies failed to provide quantitative information at the scale of the entire delta. The first general mapping study used to quantify the changes of the Camargue coastline dates from the early 1990s (L'Homer, 1992). This author gave values of coastal retreat and advance in m/yr for the decade 1980, and made a forecast for 2025. However, his results were not based on any precise methodology but simply on the compilation of the previously quoted work.

Recently, S. Suanez and B. Simon (1997) and S. Suanez and M. Provansal (1998) realised a diachronic study of shoreline change at the semi-secular scale on the eastern part of the delta, from La Gracieuse spit to the Gulf of Beauduc (fig. 1). Although these efforts have been useful in explaining patterns of shoreline behaviour, there is still a need for investigation of time-space behaviour of the entire Rhône delta shoreline. The present study aims to analyse the such change between 1895 to 2000, based on modern techniques of digital image analysis and treatment by GIS (Geographic Information System). This study provides new and more precise data on the evolution of the Rhône delta coast over a time span of more than a century. The present results also confirm the important role played by variations in the sediment input of the Rhône in controlling sediment supply to the beaches. Finally, the study shows the contribution of coastal defence structures in the protection or possible erosion of the coastline.

Environmental setting

Presentation of the site

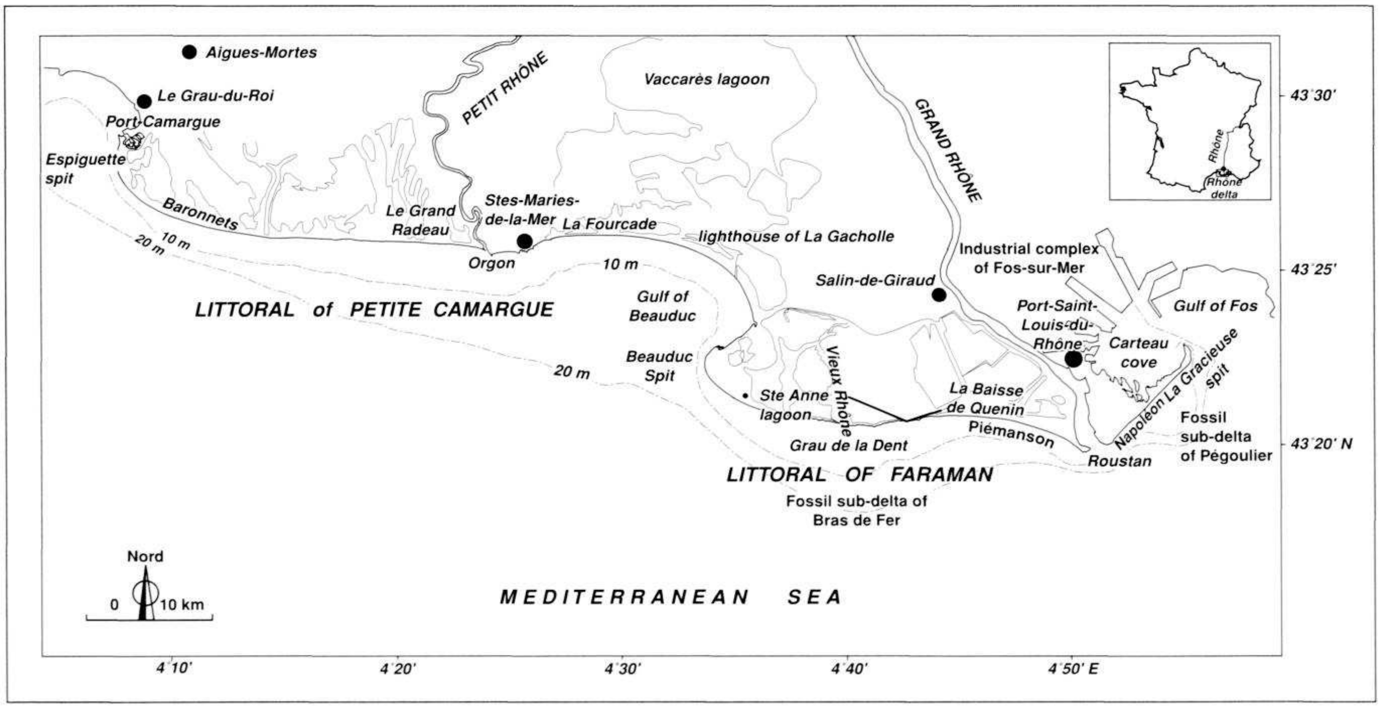
According to the classification of W.E. Galloway (1975), the Rhône delta is recognised as a wave dominated delta. The shoreline is made up of approximately 90 km of sandy barred beaches extending from La Gracieuse spit to Espiguette spit (fig. 1). The bifurcation of the river upstream of Arles gives rise to two arms: the Grand Rhône in the east, which runs into the sea at the Grau de Roustan, and the Petit Rhône in the west, whose outlet, the Grau d'Orgon, is situated to the west of Saintes-Maries-de-la-Mer. The general shape of the coastline is formed around these two arms.

The build-up of the Rhône delta plain began at around 7,000 years BP and took place in several stages (Kruit, 1955; Triat-Laval, 1978; Pons *et al.*, 1979; L'Homer *et al.*, 1981; Arnaud-Fassetta, 1998; Vella and Provansal, 2000; Vella, 2002; Provansal *et al.*, this volume). While it is outside the scope of this article to give a description of this history, it is important, nevertheless, to mention the role of: 1) sediment supply from the Rhône river in controlling the rate and degree of coastal progradation, 2) swell wave action leading to the lateral redistribution of sedimentary material, 3) variations in sea-level favouring the progradation of the coastline during regressive phases (stagnation), or on the contrary, leading to filling of the channels that partly controls avulsion of the riverbed during transgressive phases.

The current shoreline began to take its present shape from the beginning of the 18th century. Following an important flood in 1711, the Rhône of the Bras de Fer channel changed course towards the east and assumed it present-day configuration as the Grand Rhône (fig. 2). Erosion of the deltaic lobe abandoned by the shift of the channel led to the build-up of the Beauduc spit towards the west (fig. 2). During the 19th century, the position of the mouth of the Grand Rhône was directly related to human activities. From a natural configuration with three outlets (Graus de Piémanson, Roustan and Pégoulier), the mouth was artificially concentrated initially towards the southeast (Grau de Pégoulier), and then after 1892 towards the south (Grau de Roustan) (fig. 3). Since the beginning of the 18th century, successive displacements of the mouths have thus given rise to the offshore abandonment

Fig. 1 – **Location map.**

*Fig. 1 – **Carte de localisation.***



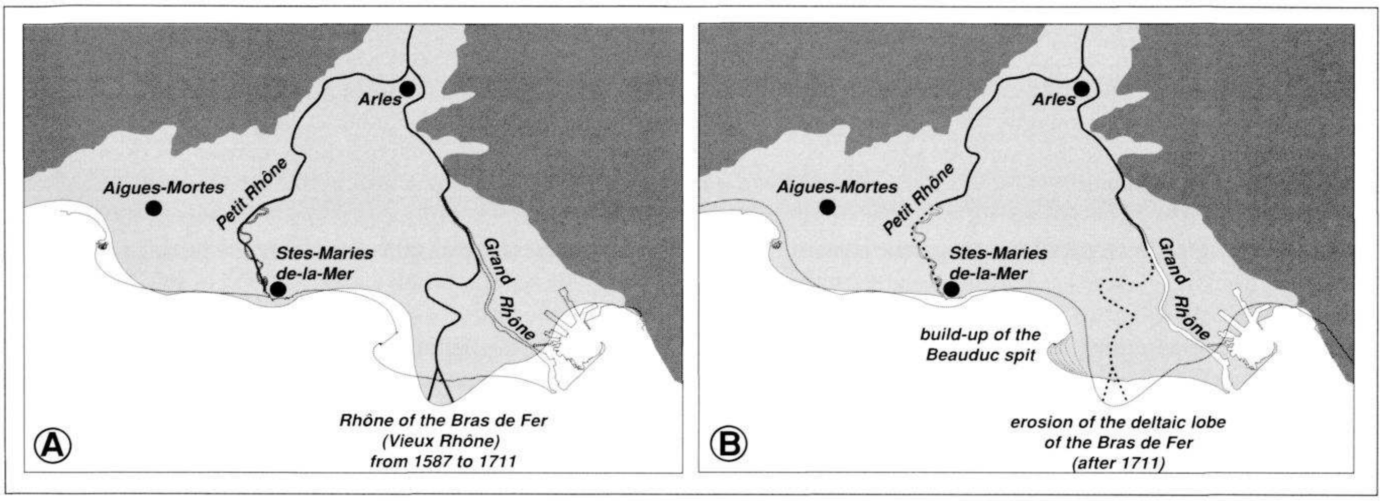


Fig. 2 – **Shifts of the Grand Rhône Channel from L'Homer *et al.*, 1981.** A: from 1587 to 1711; B: after 1711.

*Fig. 2 – **Défluvation du Grand Rhône d'après L'Homer** et al.**, 1981.** A : de 1587 à 1711 ; B : après 1711.*

Fig. 3 – **Evolution of the mouth of the Grand Rhône between 1842 and 1950**. The 1842, 1872 and 1892 maps were realised by marine hydrographic engineers of the French army (from Vernier, 1976).

*Fig. 3 – **Évolution de l'embouchure du Grand Rhône entre 1842 et 1950**. Les cartes de 1842, 1872 et 1892 ont été réalisées par les ingénieurs hydrographes de la Marine (d'après Vernier, 1976).*

of fossil sub-deltas (Bras de Fer and Pégoulier). These latter are identifiable nowadays through the lobe-type pattern of their bathymetry (fig. 1). The destruction of these fossil features by wave action releases sediment that is supplied to the present coastal zone.

Fluviatile inputs and marine dynamics

The average liquid discharge of the Rhône at Beaucaire (close to Arles) is 1,701 m^3/s. The Grand Rhône accounts for 85-90% of this discharge while the rest flows in the Petit Rhône. The suspended solid load transported by the river has been the subject of many evaluations, all of which indi-

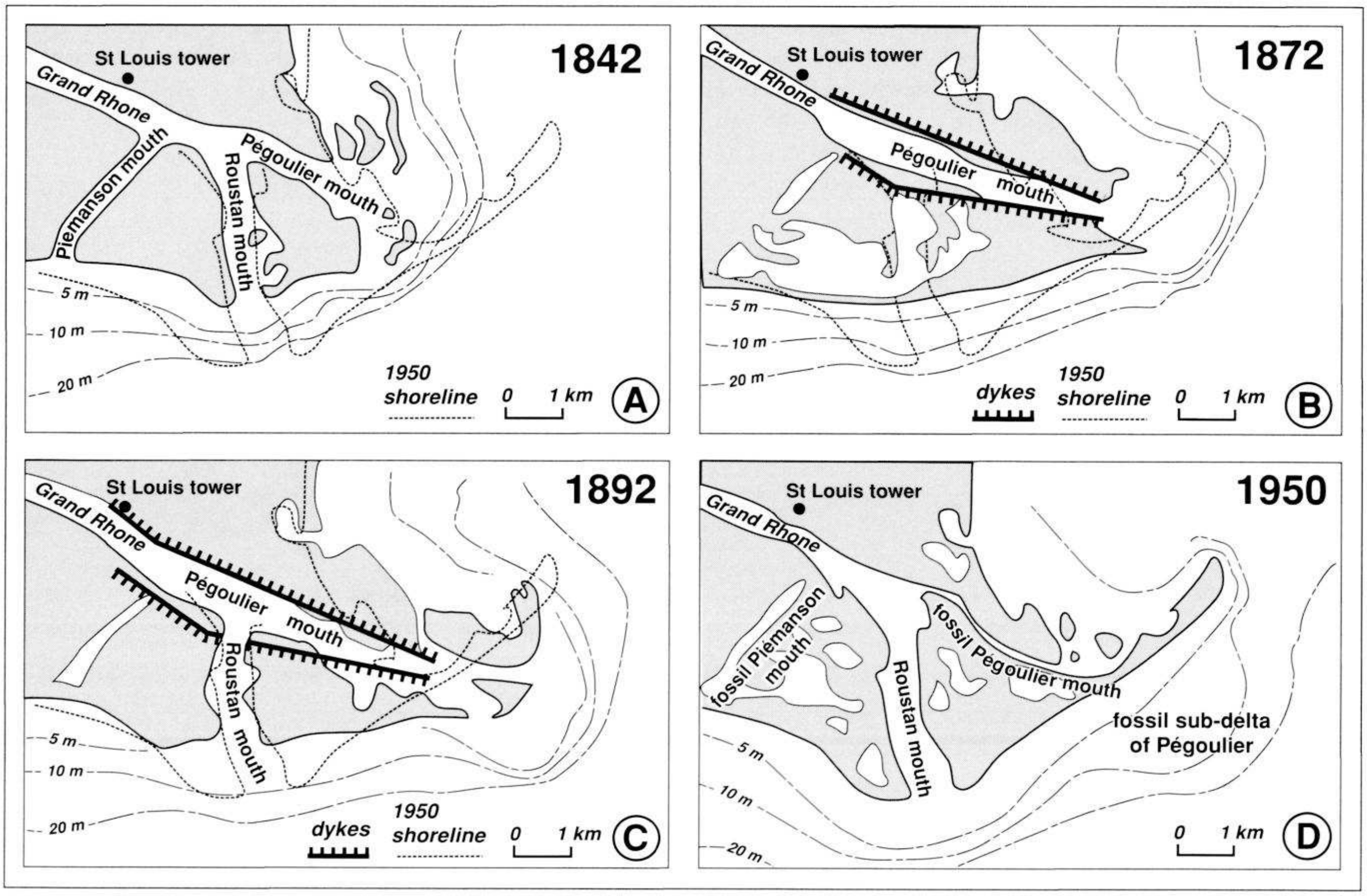
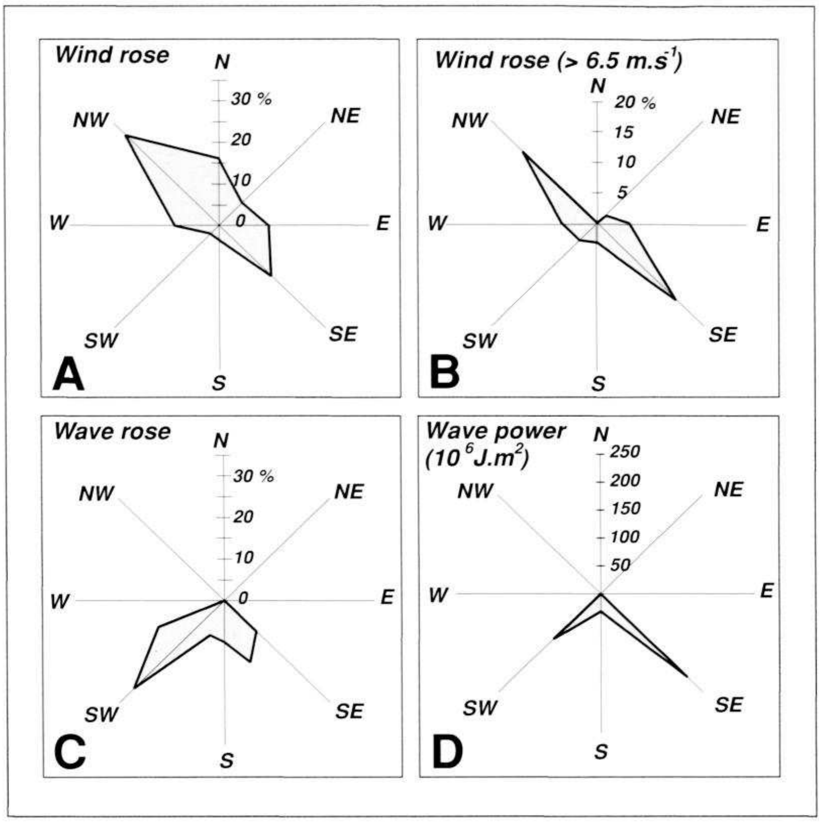


Fig. 4 – **Direction and power of winds and swell.** A: wind rose calculated from data recorded over 20 years (1962-1982) at Cap Couronne station (Greslou, 1984); B: wind rose for wind speeds exceeding 6.5 m.s⁻¹ which corresponds to the critical shear velocity (Sabatier, 2001); C: wave rose calculated from data recorded over 14 years (1964-1978) at Cap Couronne (Greslou, 1984); D: wave power rose in J.m² (Sabatier, 2001).

*Fig. 4 – **Direction et force du vent et de la houle.** A : rose des vents calculée à partir des données enregistrées sur 20 ans (1962-1982) au Cap Couronne (Greslou, 1984) ; B : rose des vents supérieurs à 6,5 m/s, valeur correspondant à la vitesse minimale d'arrachement des sables (Sabatier, 2001) ; C : rose des houles calculée à partir des données enregistrées sur 20 ans (1964-1978) au Cap Couronne (Greslou, 1984) ; D : rose de l'énergie de la houle exprimée en J.m² (Sabatier, 2001).*



cate a reduction of inputs since the 19th century. For the early 19th and 20th centuries, before the construction of dams, the suspended sediment transport has been estimated at 22.0 and 30.0 Mt/yr respectively (Surell, 1847 *in* Vernier, 1976; Pardé, 1925). Sogreah (1999) estimated the suspended sediment transport at around 13 Mt/yr between 1956 and 1958. The suspended load is currently estimated at 7.39 Mt/yr, with a minimum of 1.2 Mt/yr and a maximum of 19.7 Mt/yr (Pont *et al.*, 2002), but these values are probably under-estimated (Antonelli and Provansal, 2002). Data collected over the period 1980-2002 provide an estimate of suspended sediment transport ranging between 2.6 and 26.5 Mt/yr with an average value of 9.6 Mt/yr (Antonelli, 2002).

Several factors explain the reduction in the Rhône river input. The climatic change that occurred during the 19th century (end of the Little Ice Age) was characterised by a lower frequency of strong annual floods (Pichard, 1995), but the importance of this effect is a matter of debate by other authors (Bravard, 1989; Piégay *et al.*, 1997). The climatic effects are amplified by changes in land use in the catchment area. Agricultural decline, as well as deliberate and spontaneous reforestations, which began from the middle of the 19th century, has also played a role in the reduction of fluviatile sediment inputs. To this may be added the consequences of fluvial channel management which, from the 19th century onwards, has involved embankment and straightening, leading to the local trapping of sediments. From the 1950s and 1960s onwards, the construction of hydroelectric dams has definitively blocked off most of the coarse load, thus reducing even further the sediment flux in transit (Warner, 2000; IRS, 2001).

The Rhône delta shoreline experiences a microtidal (30 cm average range) tide range and is essentially affected by waves and the currents they generate. Waves come from two prevailing directions (fig. 4). The most frequent direction is SW (30% of the total regime), but these waves are of rather low energy with heights of 0.5 to 1 m and modal periods less than 6 s in 80% of cases. This wave direction is associated with NW and NNW offshore winds (Mistral and Tramontane). Waves from SSE and ESE represent 16% and 11% of the total annual regime, respectively. These are high-energy waves more than 2 m high in more than 40% of cases and with periods longer than 6 s in more than 25% of cases. They are associated with onshore winds from SSE and SE, whose speeds can exceed 100 km/h.

Engineering works for coastal protection

Today, more than 80% of the coastline of the Rhône delta is equipped with coastal protection structures (Suanez and Sabatier, 1999). Those having a direct impact on the coast are briefly presented here by geographical sector. Gracieuse spit has been equipped since the 1960s by the sinking of barges at the end of the spit (photo 1) to control its advance, and, since 1988, by the construction of an artificial dune ridge (Longé, 1990) (photo 2). The Faraman shore is currently equipped with 32 groynes, a breakwater and several dykes (total length of 4 km) (Caillaud *et al.*, 1990) (photo 3). While the first two rip-rap groynes were installed as early as 1941 and 1942, the intensification of engineering works started from 1987 onwards. The protection of Saintes-Maries-de-la-Mer began in the 1930s by the installation of wooden palisades. However, the coast has only been protected by hard defence structures since the 1980s (photo 4). Today, the beaches possess 3 breakwaters and 8 groynes, to which should be added a marina built in the 1980s. The coast of the Petite Camargue is equipped with several dykes (approximately 7 km total length) and a field of 122 groynes (photo 5). To the West of the Petit Rhône, most of the groynes were built between 1975 and 1989, whereas on the

Photo 1 – **Aerial view of barges stranded at the tip of La Gracieuse spit (PAM, 1997).**

*Photo 1 – **Vue aérienne des barges échouées en bout de flèche de la Gracieuse (PAM, 1997).***

eastern side of this limit, their construction dates from the years 1984-1986 and 1992-1993. At the western extremity of the Rhône delta, the Espiguette spit today provides a site for the vast marina of Camargue Port built progressively between 1968 and 1975. To protect the port entrance from the continuous silting up associated with this coastal spit, a dyke was constructed perpendicular to the coastline in 1968 and then lengthened in 1992.

Data acquisition and methodology

The oldest data were collected by EPSHOM (*Établissement Principal du Service Hydrographique de la Marine*) engineers in 1895, using the method of triangulation by means of a theodolite. The period from 1944 to 1995 is covered by aerial photography carried out mostly by the IGN (*Institut Géographique National*) at intervals of 5 to 10 years. These data are sometimes slightly diachronous from one sector to another, but they allow a satisfactory coverage of the whole delta over the last fifty years (tab. 1). The most recent survey was carried out in 2000 with a Dassault-Sercel NR51Differential GPS.

Photo 3 – **Hard coastal defence structures (rock armouring) on the littoral of Faraman at La Courbe point (from F. Sabatier, 1999).**

*Photo 3 – **Ouvrages de défense côtière sur le littoral de Faraman à la pointe de la Courbe (cliché F. Sabatier, 1999).***

Photo 2 – **Aerial view of the artificial dune on La Gracieuse spit (from M. Cotte, PAM, 1997).**

*Photo 2 – **Vue aérienne du cordon artificiel de la flèche de la Gracieuse (cliché M. Cotte, PAM, 1997).***

Digital processing

The treatment of the aerial photographs is based on classical methods used in many studies (Dolan *et al.*, 1978; Levoy,

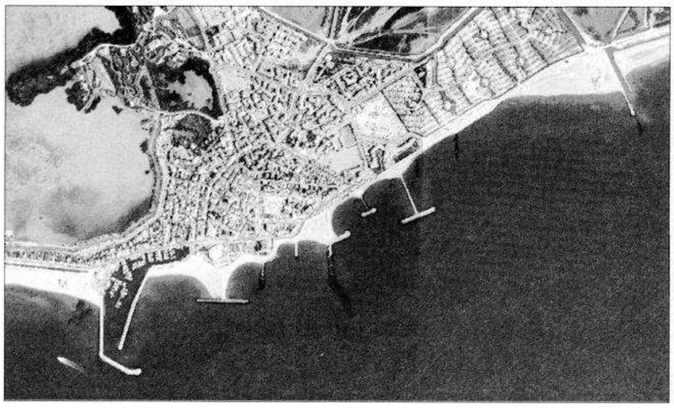


Photo 4 – **Hard coastal defence structures (groynes) on the littoral of Saintes-Maries-de-la-Mer (Aérial, 1992).**

*Photo 4 – **Ouvrages de défense côtière sur le littoral des Saintes-Maries-de-la-Mer (Aérial, 1992).***

Table 1 – **Data used for analyses of secular shoreline change.**

Table 1 – ***Sources utilisées pour l'analyse des changements séculaires du trait de côte.***

Date	Type of data	Source
1895	Levelling of terrain by theodolite	EPSHOM (Brest)
1944	Aerial photography (scale 1 : 15,000)	Centre Camille Julian (University of Provence)
1953-1954-1955	Aerial photography (scale 1: 25,000 and 1: 30,000)	IGN
1960-1962	Aerial photography (scale 1: 25,000 and 1: 30,000)	IGN
1977-1979	Aerial photography (scale 1: 25,000 and 1: 30,000)	IGN
1987-1989-1990	Aerial photography (scale 1: 25,000 and 1: 30,000)	IGN
1994-1995-1996	Aerial photography (scale 1: 25,000 and 1: 30,000)	IGN
1998	Aerial ortho-photography (resolution 50 cm)	IGN
2000	Differential GPS	Sabatier (2001)

1989; Shoshany et Degani, 1992; Paskoff, 1994; Jimenez *et al.*, 1997; Durand, 1998, 2000; Robin, 2002). The instantaneous coastline is drawn manually on polyester tracing film by photo-interpretation. The data entry is performed using a stereophony-zoom-transferscope (trademark Bauch and Lomb) that can enlarge up to 20 times, thus avoiding the problems of different scales between photographs. This apparatus also makes it possible to rectify all the deformations and distortions produced at the time of taking the shots. The geometrical correction is made from a reference document consisting of the IGN topographic map at 1:25,000. The copies are then scanned at very high resolution (600 dpi), and the information is finally digitised and georeferenced in Lambert III co-ordinates with a GIS (MapInfo 6.5).

Photo 5 – **Groyne field on the littoral of Petite Camargue (from *Service Maritime et de Navigation du Languedoc-Roussillon*, 1998).**

Photo 5 – ***Batterie d'épis sur le littoral de la Petite Camargue (cliché du*** **Service Maritime et de Navigation du Languedoc-Roussillon,** ***1998).***

For the field notes of 1895 and the surveys carried out in 2000, the position of the coastline corresponds to the upper limit of the instantaneous swash. The data from the 19th century were scanned, digitised and georeferenced in Lambert III co-ordinates by the cartographic service of EPSHOM. Data collected in 2000 were entered from the original in WGS84, and then also transformed into Lambert III in order to homogenise them.

The complete dataset derived from photo-interpretation and field surveys was compiled in a GIS (MapInfo 6.5), and then used to calculate the distances of coastline retreat or advance, as well as the areas lost or gained by the littoral fringe.

Estimation of error margin

The siting of fixed points (landmarks or invariable features) present on all the photographs (buildings, works, road crossings, etc.) enables us to define, after superposition, a margin of error varying from 16 m to 4 m according to the date. This error is primarily related to the more or less precise adjustment of the aerial photographs compared with the reference document. The quality and the scale of the shots are the parameters that control this precision. The largest errors relate to the older periods (1944 and 1953), for which an average value of ± 10 m is accepted. This agrees with the thresholds proposed by several authors (Crowell *et al.*, 1991; Shoshany et Degani, 1992; Durand, 2000; Robin, 2002).

It appears much more problematic to estimate the error margin for the position of the shoreline in 1895. According to EPSHOM services, the surveying techniques used from

Photo 6 – **Dyke for blocking sands at the top of Espiguette spit (*Aérial*, 1992).**

Photo 6 – ***Digue d'arrêt des sables sur la pointe de la flèche de l'Espiguette (Aérial, 1992).***

the end of the 18th century are highly reliable. Initiated by the engineer Charles François Beautemps-Beaupré, these measurements were taken by triangulation using a theodolite coupled to a hydrographic circle. Positioning is carried out from landmarks materialised by beacons installed on firm ground. The measuring precision is estimated at ± 10 m.

For the surveys carried out by DGPS in 2000, the planimetric error margin for the coastline position in 2000 is close to ± 3 m.

Results

Changes of shoreline position

The variations of the coastline are analysed from 98 profiles drawn perpendicular to the shore (fig. 5A).

The most important shoreline changes along the Rhône delta coast are in the vicinity of the mouth of the Grand Rhône, with the construction of La Gracieuse spit during the

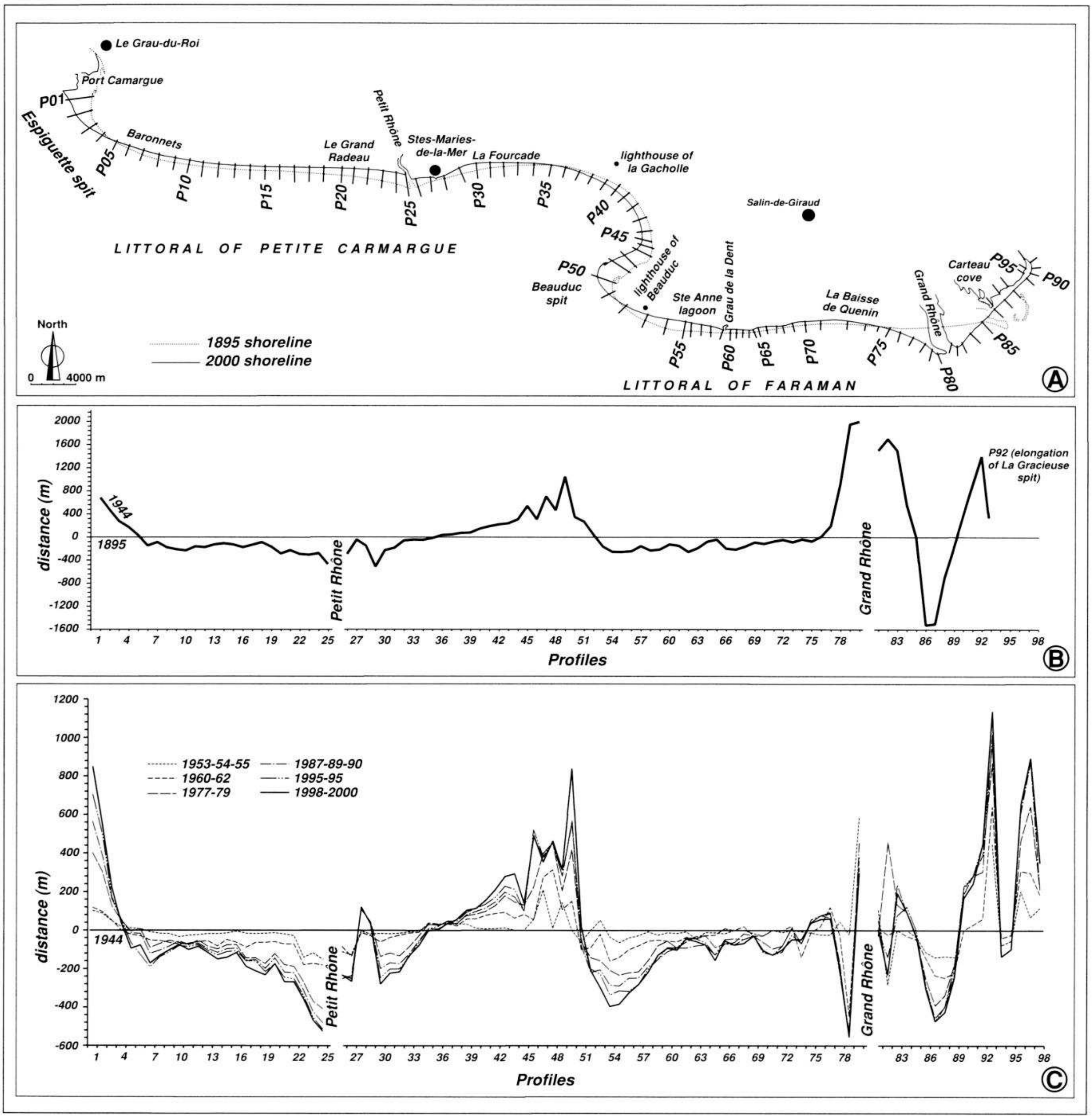


Fig. 5 – **Shoreline changes between 1895 and 2000**. A: position of profiles; B: shoreline changes between 1895 and 1944; C: shoreline changes between 1944 and 2000.

*Fig. 5 – **Variations du trait de côte entre 1895 et 2000**. A : position des profils ; B: variations du trait de côte entre 1895 et 1944; C: variations du trait de côte entre 1944 et 2000.*

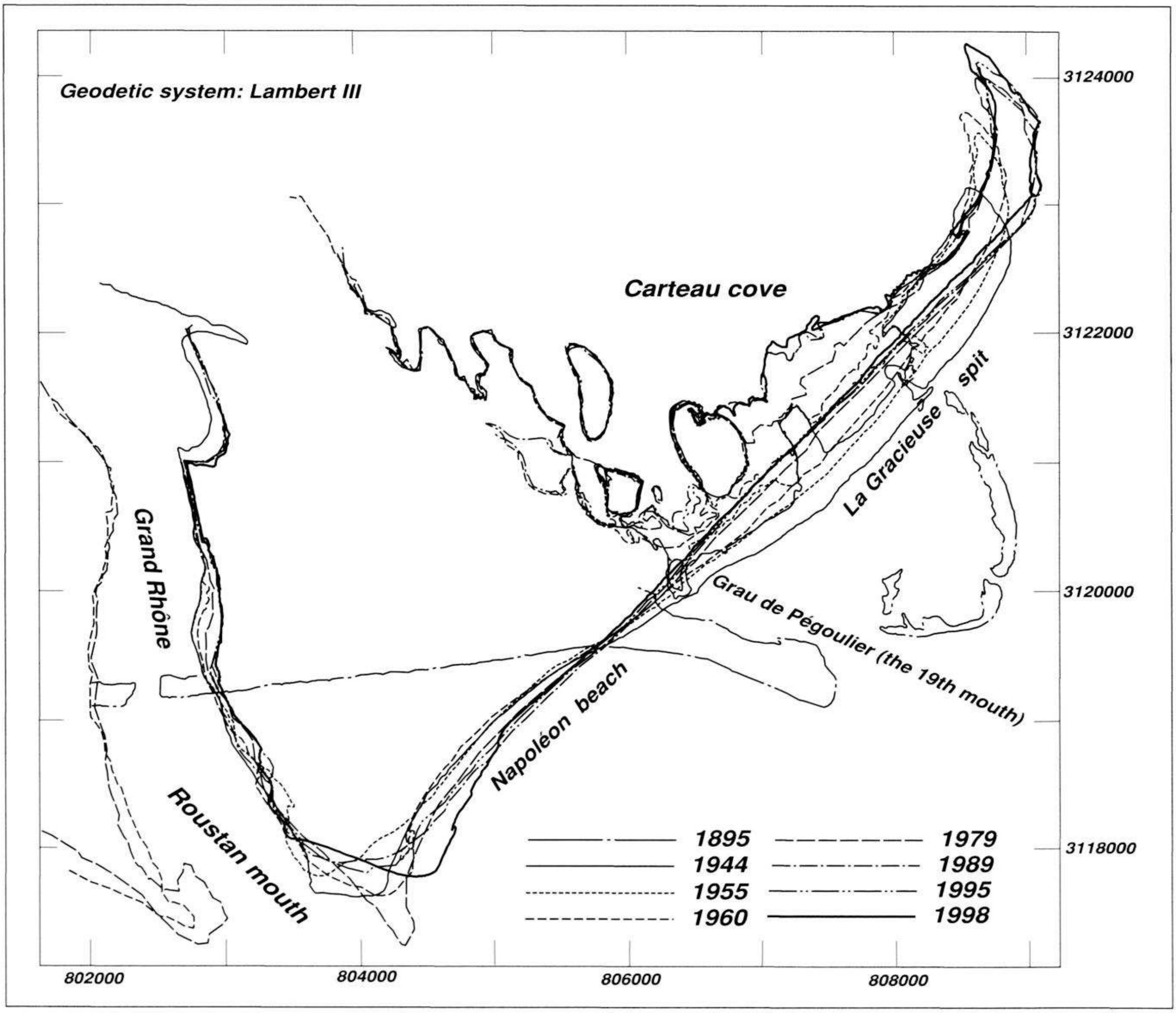
20th century. After the Rhône mouth switched from Pégoulier to Roustan in 1892, the massive destruction of the prodeltaïc lobe of Pégoulier induced a shoreline retreat of about 1,500 m between 1895 and 1944 (fig. 5B). Meanwhile Gracieuse spit became elongated to the northeast, growing by 1,400 m until 1944 (fig. 6). At the same time, Piémanson and Napoléon beaches, located on either site of the mouth, underwent rapid progradation, of the order of 1,500 m and 1,700 m respectively. From 1944 to 1998, Gracieuse spit lengthened by a further 1,200 m, but its central part experienced a retreat of about 400 m, while Napoléon beach prograded about 120 m (fig. 5C).

To the west of the mouth of the Grand Rhône, the Faraman shoreline exhibits two sectors marked by different patterns of evolution (fig. 7). Between 1895 and 1960-1962, Piémanson beach (profiles P77 to P74) is subject to erosion (fig. 7A). The rather slow rates of retreat oscillate between -1 and -15 m/yr according to the sector and period. After the 1960s, the trend is reversed. The regularisation of the coastline towards a rectilinear shape is due to the progradation processes with rates ranging between +2 and +7 m/yr. Generally speaking, profile 74 corresponds to a hinge point, after which is observed a transition into a zone of constant erosion since 1895. This zone extends from Baisse de Quenin to Beauduc light house (fig. 7B). To the east of Grau de la Dent (P75 to P60), erosion rates are between -2 and -3 m/yr over the whole of the period, corresponding to a maximum secular retreat of -250 m in the western sector of Baisse de Quenin (P70-P71). To the west of Grau de la Dent (fig. 7C), the erosion of the shoreline is more rapid, with rates of between -2 and -8 m/yr over the whole of the period. Maximum erosion is recorded at profile 54, where the beach has moved back by approximately 650 m since 1895.

The spit and gulf of Beauduc have been subject to important sedimentation (P51 to P35). There has been a secular

Fig. 6 – **Shoreline changes of La Gracieuse spit and Napoléon beach between 1895 and 1998.**

*Fig. 6 – **Variations du trait de côte de la flèche de la Gracieuse et de la plage Napoléon entre 1895 et 1998.***



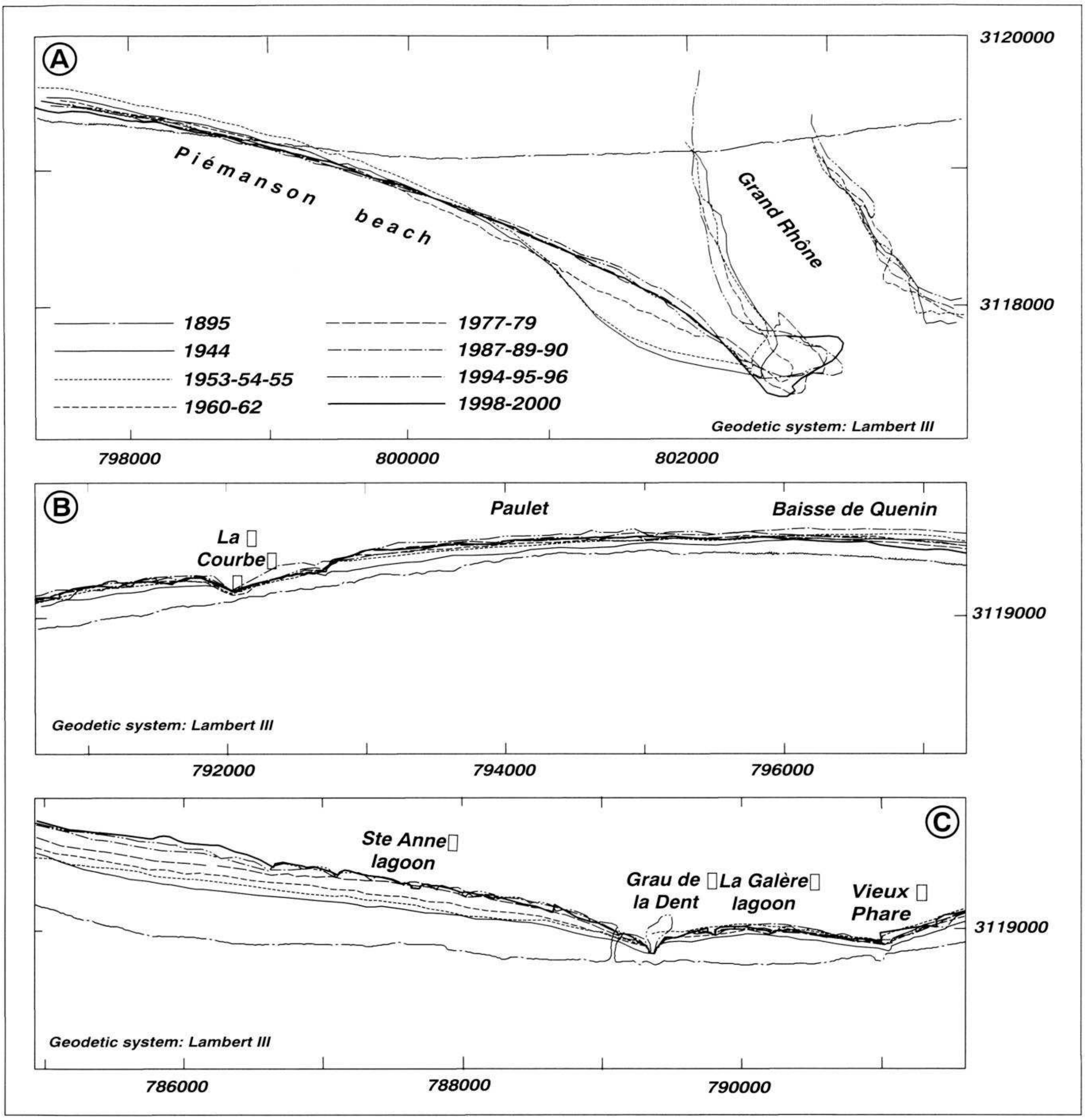
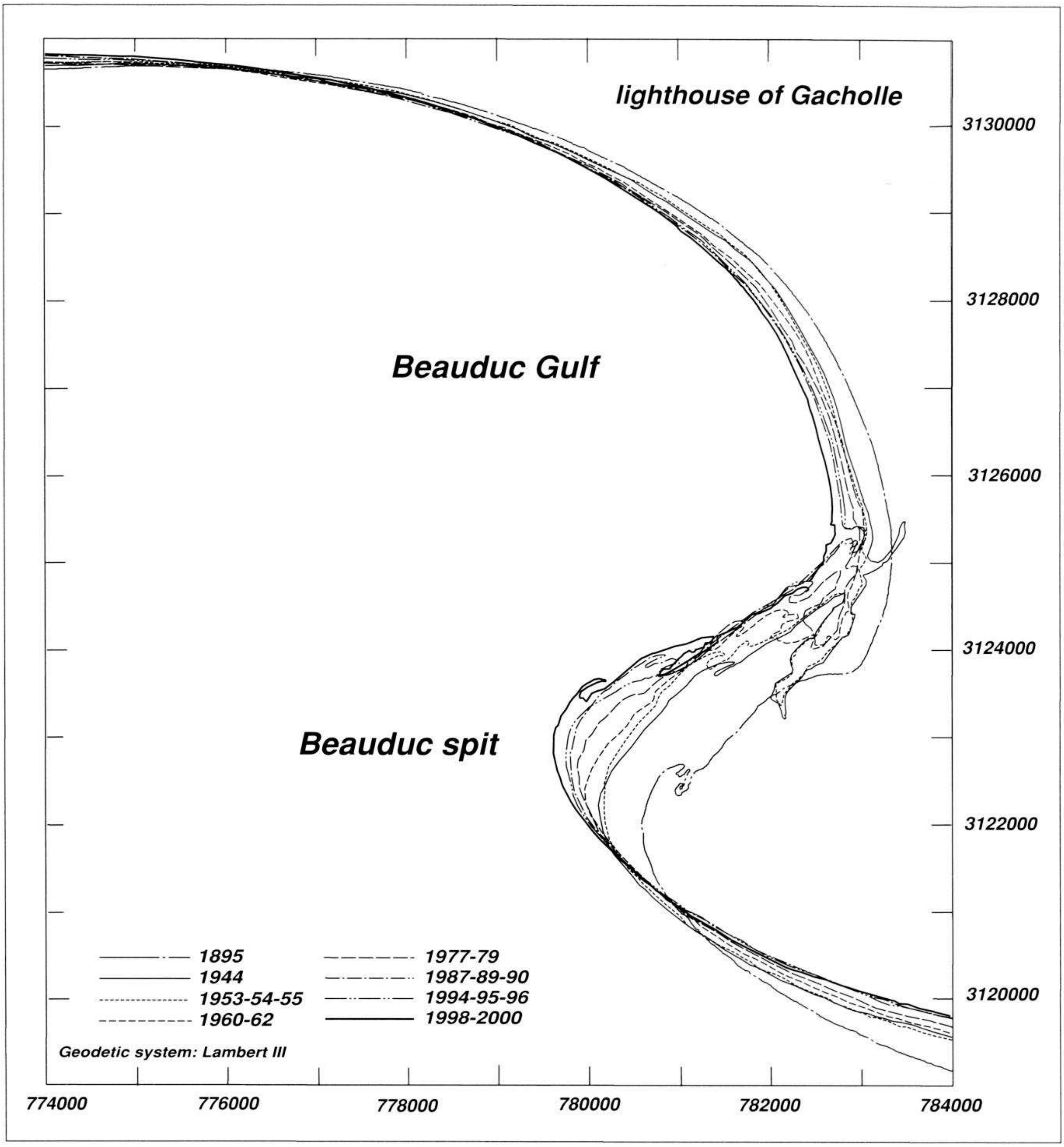


Fig. 7 – **Shoreline changes on the littoral of Faraman between 1895 and 2000.**

*Fig. 7 – **Variations du trait de côte du littoral de Faraman entre 1895 et 2000.***

advance of the shoreline of approximately +1,500 m on the axis of Beauduc spit (P50) (fig. 8). These very high rates of progradation vary between +7 and +15 m/yr at the spit, but are lower in the gulf, with values between +1 and +6 m/yr.

From the lighthouse of La Gacholle to Baronnets, the coast of Saintes-Maries-de-la-Mer and Petite Camargue has been in constant erosion since 1895 (figs. 9A and 9B). This area is subject to considerable coastal retreat that threatens the socio-economic activities situated behind the shoreline, and has undergone the most extensive development of artificial environments in the delta since the 1980s (photos 4 and 5). From the lighthouse of Gacholle to the eastern part of the village of Saintes-Maries-de-la-Mer, the rates of coastal erosion increase, with values ranging from -1 m/yr in the east to -5 m/yr in the sector of La Fourcade where the coastline has moved back more than 500 m since 1895 (P30). The pattern of variation shows that the retreat remained around -3 m/yr between 1895 and the 1960s, and then accelerated to -5 m/yr from 1963 onwards. The shoreline of the village of Saintes-Maries-de-la-Mer initially underwent the same evolution. However, the trend is reversed from the 1970s on-



wards as coastal defences were emplaced (photo 5). The coastline near the mouth of the Petit Rhône (P25 to P21) shows the maximum amount of retreat observed in the Rhône delta since 1895. It reaches more than 1,000 m at the level of profile 25, with rates ranging between -3.5 and -10 m/yr according to the sector. This erosive trend continues towards the west, between the sectors of Grand Radeau and Baronnets (P20 to P6), but the rate of retreat gradually decreases to between -1 and -4 m/yr. For the entire coast west of the mouth of the Petit Rhône, however, the retreat is slower from the 1980s onwards.

Fig. 8 – **Shoreline changes on the spit and gulf of Beauduc between 1895 and 2000.**

*Fig. 8 – **Variations du trait de côte du littoral de la flèche et du golfe de Beauduc entre 1895 et 2000.***

As observed in the case of the Beauduc spit, the Espiguette spit (P5 to P1) is marked by a constant progradation of the coast (fig. 10). In this sector, we find the highest values of coastline advance (+1,500 m at profile P1) on the scale of the entire delta.

Spatial variations in coastal surface area and sediment budget

The evolution of the surface area in different sectors confirms the results obtained on coastline changes. The secular evolution of land areas gained or lost on the littoral fringe enables identification of three periods (fig. 11). The Camargue coast records a gain of 3,875,600 m^2 between 1895 and 1944, a loss of 1,707,800 m^2 between 1944 and 1987-1990, and a gain of 209,600 m^2 between 1987-1990 and 1998-2000. The surface area determined over the scale of the century thus shows a net gain of about 2,377,400 m^2.

Five zones exhibit a rather homogeneous behaviour irrespective of the period (fig. 12). Espiguette spit and the Beauduc sector have increased by 46,500 and 66,000 m^2/yr, respectively (average values calculated for the whole century). On the contrary, a continuous surface area loss is recorded in the sectors located west of Grau de la Dent, from La Gacholle to the Petit Rhône and from the Petit Rhône to Baronnets, with average values of -33,000 m^2/yr, -69,000 m^2/yr and -30,000 m^2/yr, respectively. The four zones located on either side of the mouth of the Grand Rhône (fig. 12) show a more irregular behaviour marked by periods of gain or retreat.

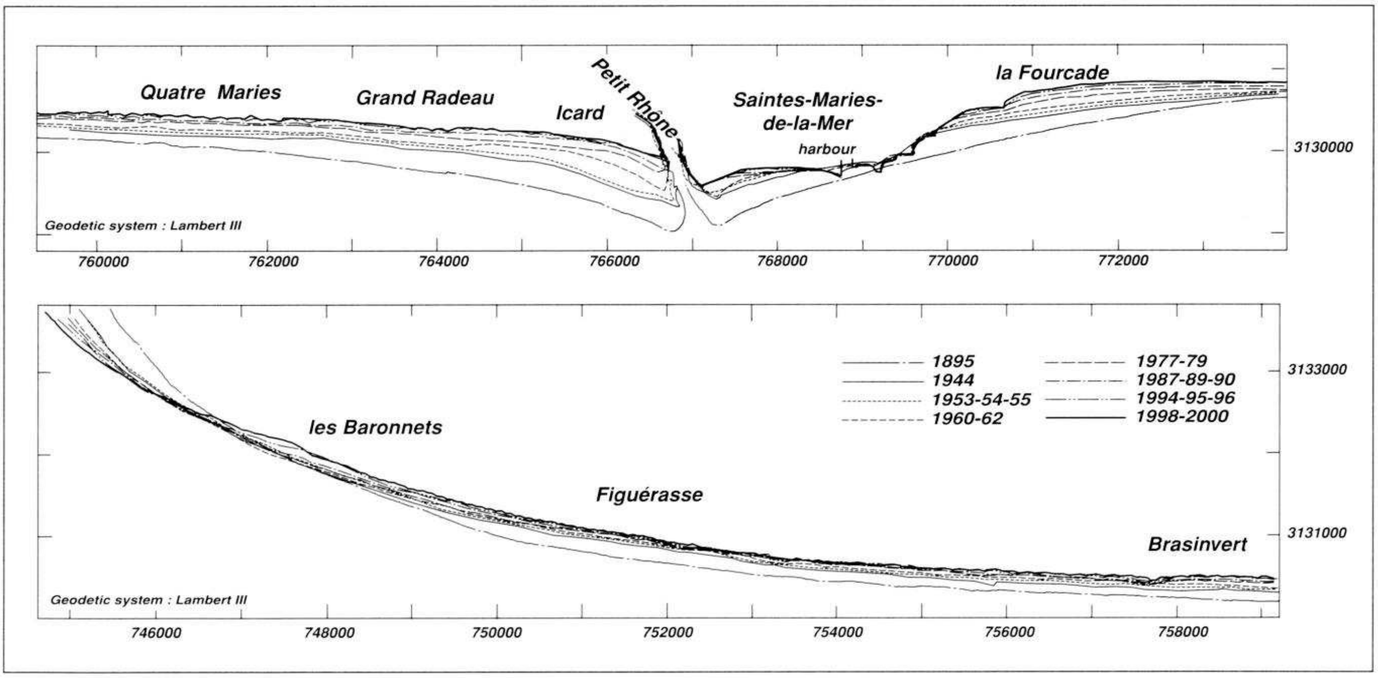
Discussion

Efficiency of coastal defence structures in maintaining shoreline position

The artificial dune built in1988 to stabilise the central part of Gracieuse spit and the barges stranded at the end of the spit presently control the general shape of this feature. Along Faraman shore, the coastline was stabilised at the end of the 1980s (period 1989-1990). This change of behaviour is explained by the emplacement, from 1987 onwards, of hard coastal defence structures constructed by the *Compagnie des Salins du Midi et des Salines de l'Est* (photo 3). While this policy of coastline stabilisation proved satisfactory (Suanez et Bruzzi, 1999), other poorly protected sectors retreated again after 1992. The coastal structures along the village of Saintes-Maries-de-la-Mer have stabilised the shoreline since the 1970s but induced erosion on the eastern part since the 1960s (La Fourcade). In this case, the coastal structures trap sediment transported by longshore currents from west to east and thus starve la Fourcade beach which erodes. Along the Petite Camargue, the field groynes (photo 5) built in 1975 and 1984-86 reduced shoreline retreat but these structures have yielded less satisfactory results than along Faraman shore. Two factors explain these results. First, the spacing between groynes along the Petite Camargue is probably too large (Sabatier, 2001) and second, the Faraman coast receives more sediment because of the proximity of the fossil sub-delta of Bras de Fer whose erosion sources the surf zone (Suanez et Bruzzi, 1999). On Espiguette spit, sedimentation became all the more important during the 1970s, when a dyke was built at the end of the spit to block longshore sediment transport. It was constructed to prevent silting up of the entrance to Port Camargue marina. Since the end of the 1990s, this dyke is gradually bypassed by sand due to shoreline advance (photo 6). In general, the coastal structures enable fixing of the shoreline position or reduction of shoreline retreat but submarine erosion continues. The long term efficiency of these structures is thus not clear (Paskoff, 1998; Sabatier and Provansal, 2000, 2002).

Fig. 9 – **Shoreline changes on the littoral of Saintes-Maries-de-la-Mer and the Petite Camargue between 1895 and 2000.**

Fig. 9 – ***Variations du trait de côte du littoral des Saintes-Maries-de-la-Mer et de la Petite Camargue entre 1895 et 2000.***



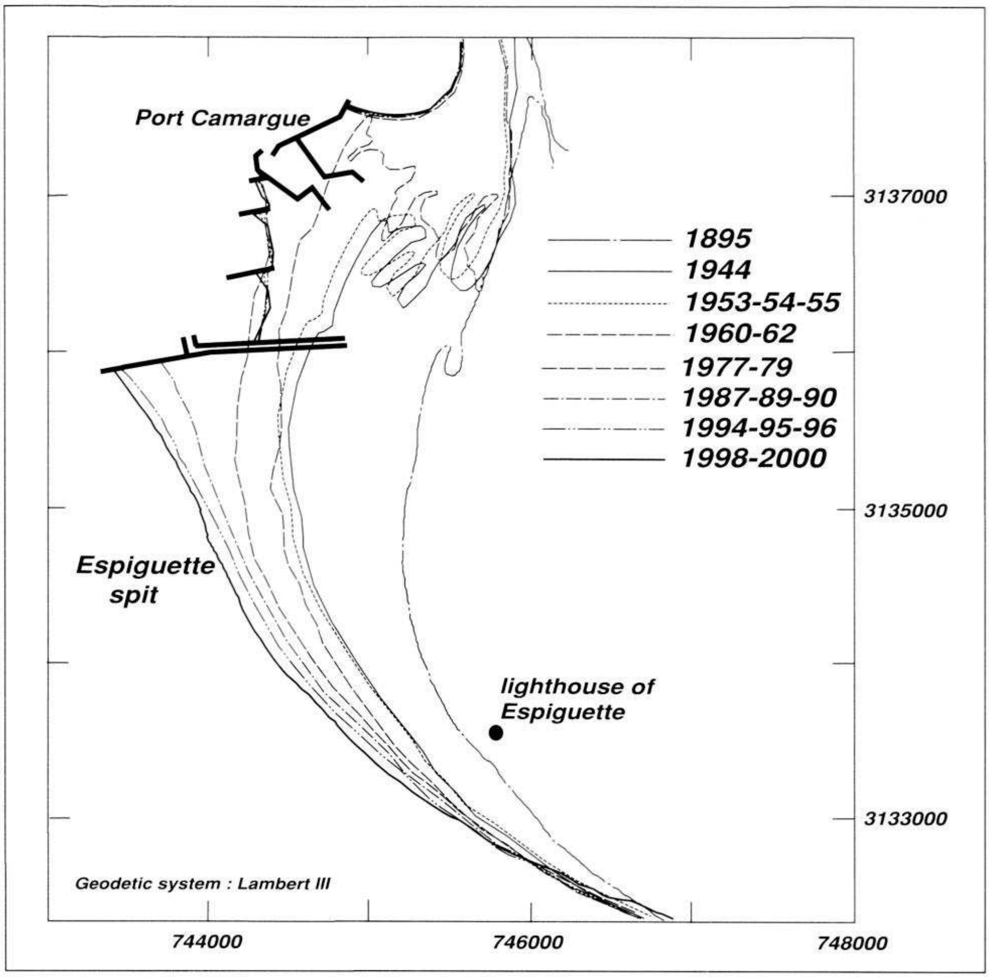


Fig. 10 – **Shoreline changes on Espiguette spit between 1895 and 2000.**

*Fig. 10 – **Variations du trait de côte de la flèche de l'Espiguette entre 1895 et 2000.***

River sediment contribution to the shoreline position

Along the whole delta coast, the large increase in land area recorded between 1895 and 1944 (fig. 11) can be explained by an abundant supply of sediment to the coast. In spite of the relative reduction in the frequency of annual floods (Pichard, 1995), the persistence of mountain agricultural land use and incomplete reforestation in the catchment basin accounted for the continuing abundance of solid load before the era of hydroelectric dams. After 1944, the agricultural decline accelerated and the vegetation cover of the Rhône catchment became more extensive, particularly near the banks, where riverine plants effectively trap sands and silts (Bravard, 1989; Jorda and Provansal, 1996; Miramont and Guilbert, 1997; Piégay *et al.*, 1997; Warner, 2000). The reduction in the area of bare soil involved a decrease in the sediment supply, which became even more marked in the years 1950-1960 due to the construction of hydroelectric dams that blocked much of the coarse load of the watercourses (Klingeman *et al.*, 1994; Gautier, 1994; IRS, 2001). This phenomenon was accentuated by the decline in river liquid discharge during these decades and the decreased frequency of floods (Pichard, 1995; Antonelli, 2002; Pont *et al.*, 2002; Arnaud-Fassetta 2003). These factors explain the reversal of the trend observed between 1944 and the late 1980s. During this period, the coastal fringe of the Rhône delta underwent a deficit in sediment input that resulted in shoreline erosion and in a loss of surface area. The increase in surface area recorded on the Camargue coastal fringe between 1987-1990 and 1998-2000 demonstrates the effectiveness of coastal defence structures in slowing down coastline retreat as discussed above.

River sediment contribution to the shoreline is highlighted in figure 12. The chaotic-type behaviour of sectors close to the mouth of the Grand Rhône (fig. 12) is explained by the

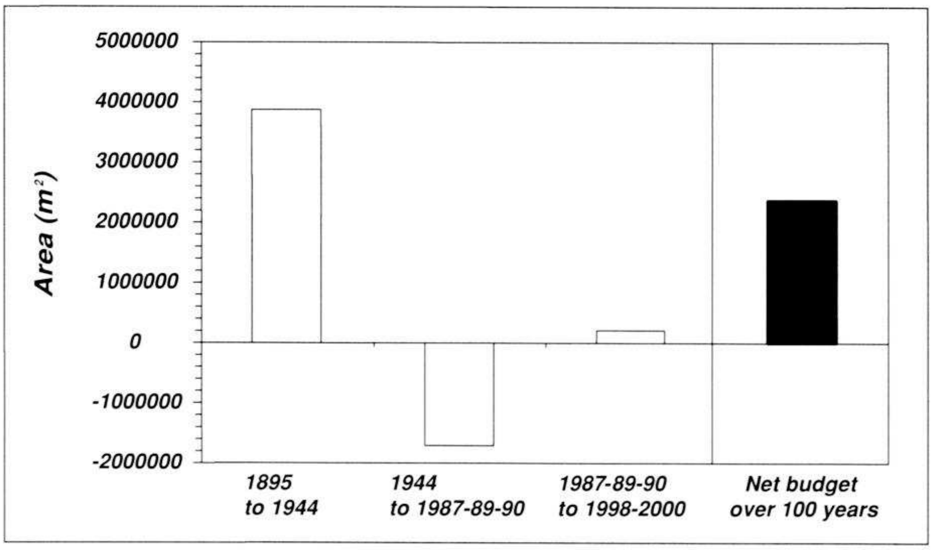


Fig. 11 – **Secular evolution of the surface area of different homogeneous sectors.**

*Fig. 11 – **Evolution séculaire des variations de surface de la frange littorale par secteurs homogènes.***

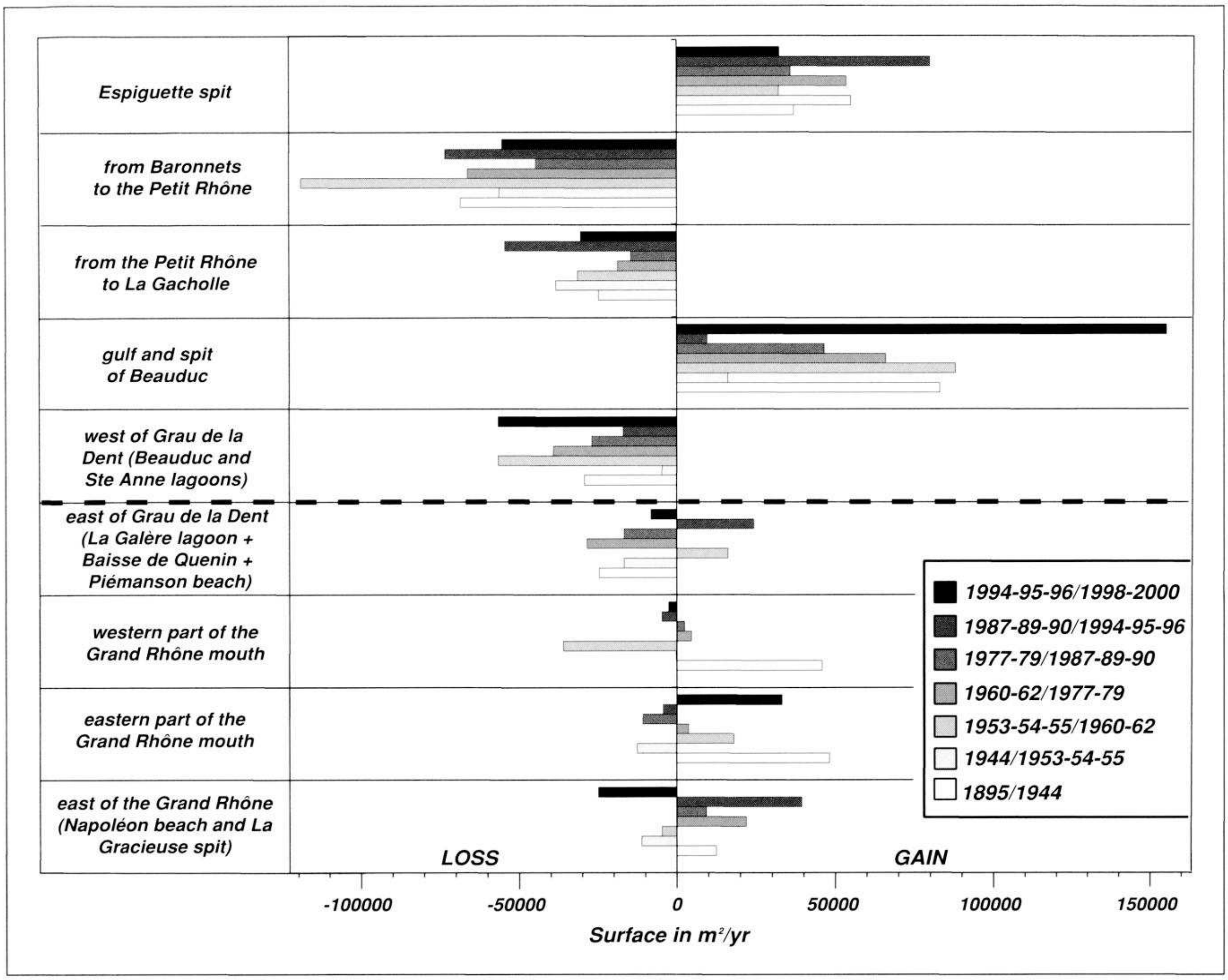


Fig. 12 – **Secular evolution of the surface area of the Rhône delta coastal fringe.**

*Fig. 12 – **Évolution séculaire de la frange littorale du delta du Rhône exprimée en surface.***

strong interannual variability of the sediment input from the river. The redistribution of these sediments by longshore drift, after temporary storage in the vicinity of the mouth, is probably offset in time from one sector to another. However, with increasing distance from the mouth of the Grand Rhône (fig. 12), the continuous development of sectors in erosion and accretion suggests that longshore drift assumes greater importance. A number of permanent zones can thus be distinguished wherein sediment erosion is predominant (west of Grau de la Dent, from the Petit Rhône to Baronnets and from Gacholle to the Petit Rhône), in contrast with zones where deposition is predominant (Espiguette spit and the Beauduc sector). This distribution indicates an organisation of the Rhône delta shoreline based on longshore drift cells.

Longshore drift cells

The longshore drift pattern is based on the identification of four cells, each of which is defined by an accretion zone (spits, gulf and Roustan mouth) supplied by a zone undergoing erosion (May and Tanner, 1973; Stapor, 1974; Carter, 1988; Komar, 1998). While longshore sediment transport is the major process reshaping the Rhône delta coastline, cross-shore processes also exist, but these cannot be quantified using shoreline change analysis. The cell definition pattern presented here is based on the pattern of evolution of the Rhône delta. However, it is confirmed by simulations of longshore sediment transport using empirical equations (Sogreah, 1995).

The easternmost cell (CEL1) is located east of the Grand Rhône, where the prevailing sediment transport is eastward (fig. 13). It is bounded on its western side by the mouth of the Rhône, and on its eastern side by the La Gracieuse spit. This cell is thus fed by the present-day inputs of the Rhône (active source) and by the erosion of the fossil deltaïc lobe of Pégoulier (Suanez, 1997; Suanez *et al.*, 1998).

The second cell (CEL2) also shows a general direction of transport from west to east, and extends from Ste-Anne lagoon as far as Grau de Roustan (fig. 13). Although the shoreline retreat in this zone contributes to the supply to Piémanson beach, part of the eroded material is stored in the

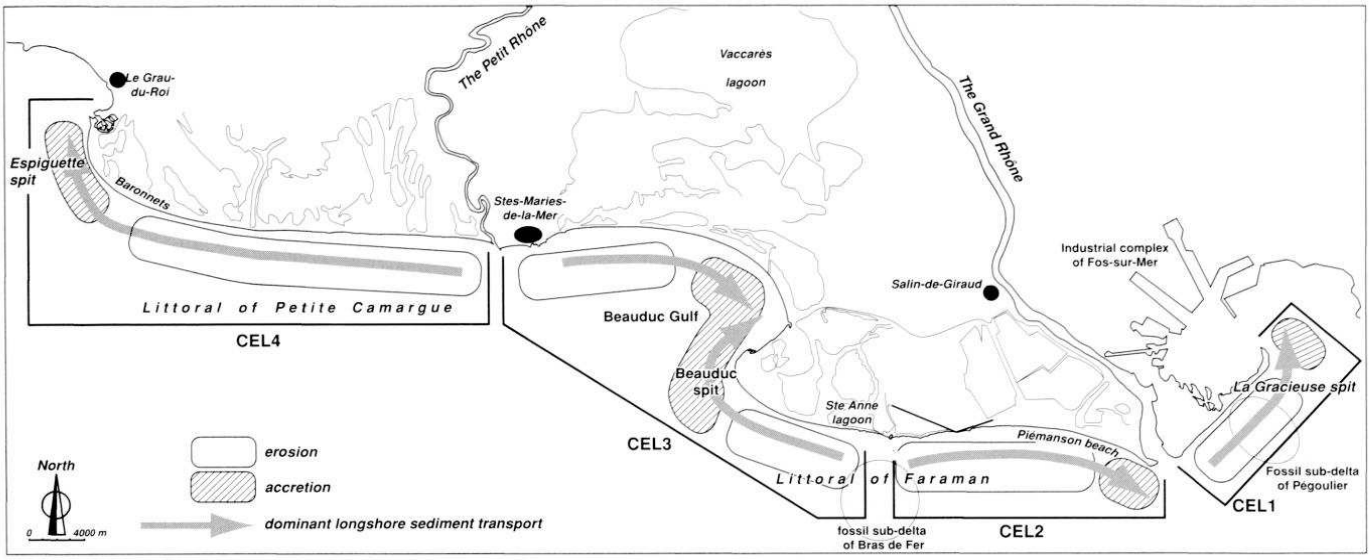


Fig. 13 – **The littoral cell pattern on the Rhône delta coast.**

Fig. 13 – ***Organisation des cellules littorales le long du delta du Rhône.***

vicinity of the Roustan prodelta, considered as an important sediment sink (Suanez *et al.*, 1998) The limit between cells 2 and 3, located generally near Ste Anne lagoon, is explained by a reversal of the longshore drift along with sediment transport as a result of refraction of swell on the fossil deltaic lobe of the Bras de Fer (Sabatier, 2001).

The third cell 3 (CEL3) extends from Ste Anne lagoon in the east as far as the Petit Rhône in the west (fig. 13). This cell is made up of a central part subject to accumulation (spit and gulf of Beauduc), fed in the east by the retreat of the beaches and erosion of the fossil sub-delta of the Bras de Fer, and in the west by erosion of the beaches in the Saintes-Maries-de-la-Mer sector. Thus, drift convergence associated with the two eroded sectors results in an important sediment sink in the very centre of the delta. Sediment supply to Gulf of Beauduc via the Petit Rhône is extremely limited, being dependent on the very weak sand inputs of this arm (Arnaud-Fassetta, 1996, 1997; Arnaud-Fassetta *et al.*, 2003).

To the west of the Petit Rhône, the fourth cell (CEL4) is defined by a dominant sediment transport directed towards Espiguette spit (fig. 13). As seen on the littoral of Faraman, the opposite sediment transport directions in cells 3 and 4 can be explained by the divergence of the longshore drift related to refraction of swell on the prodelta of the Petit Rhône (Sogreah, 1995; Sabatier, 2001). The sector in erosion from the Petit Rhône to Baronnets contributes to sandy inputs to the spit, which may also be considered as a sand sink (Blanc, 1977; Sabatier and Raivard, 2002).

Conclusion

This study updates our knowledge of the changes that have affected the Rhône delta coastline over the past 105 years. The use of digital processing techniques has been instrumental in integrating and managing, via a Geographic Information System, the large database compiled from the analysis of various sources. The results of this work enable the drawing up of maps aimed at the prevention of erosion risks, and the proposal of these tools as aids to decision-making in coastal management.

These results also show the close link between the Rhône catchment area and the littoral fringe of the Rhône delta. The secular evolution of the coastline near the mouth clearly records variations in fluvial sediment input, but it remains difficult to separate the effects of hydrological changes (end of the Little Ice Age) from modifications due to changing land use or hydraulic engineering works. The beaches close to the Grand Rhône mouth are dependent on the river sediment input but the erosion of fossil sub-deltas plays also an important role in feeding the spits.

Finally, the results highlight the important role played by coastal defence structures in the current dynamic status of large parts of the coastline. These has been a heated debate about their long-term effectiveness, especially in view of the forecasts of sea-level rise and the poorly known long-term evolution of the submerged shoreface profile (Suanez and Provansal, 1996; Paskoff, 1998, 2001; Suanez and Sabatier, 1999; Provansal and Sabatier, 2000; Picon and Provansal, 2002). In such a context, several stake-holders in coastal management have put forward the idea of a strategic withdrawal of activities and settlement assets in certain sectors (*Conservatoire du Littoral, Parc de la Camargue, Réserve Nationale de Camargue*). This position is evidently badly accepted by the local residents and inhabitants of Saintes-Maries-de-la-Mer, and by the salt extraction industry and farmers of the Petite Camargue. The pursuit of scientific monitoring and analysis should enable politicians and managers to make decisions with a fuller knowledge of the coastal processes.

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References

Antonelli C. (2002) – *Flux sédimentaires et morphogenèse récente dans le chenal du Rhône aval.* Thèse de Doctorat, université de Provence, Aix-Marseille I, 279 p.

Antonelli C., Provansal M. (2002) – Vers une ré-évaluation des matières en suspension du Rhône aval par acquisition de mesures sur toute la colonne d'eau. *Proceedings of Geomorphology: from expert opinion to modelling*, Strasbourg, France, 141-148.

Arnaud-Fassetta G. (1996) – Les inondites rhodaniennes d'octobre 1993 et janvier 1994 en milieu fluvio-deltaïque. L'exemple du Petit Rhône. *Quaternaire*, 7 (2-3), 139-153.

Arnaud-Fassetta G. (1997) – Évolution du plancher alluvial du Petit Rhône à l'échelle pluri-annuelle (delta du Rhône, France du Sud). *Géomorphologie : relief, processus, environnement*, 3, 237-256.

Arnaud-Fassetta G. (1998) – *Dynamiques fluviales holocènes dans le delta du Rhône.* Thèse de Doctorat, université de Provence, Aix-Marseille I, 328 p.

Arnaud-Fassetta G. (2003) – River channel changes in the Rhône Delta (France) since the end of the Little Ice Âge: geomorphological adjustment to hydroclimatic change and natural resource management. *Catena*, 51 (2), 141-172.

Arnaud-Fassetta G., Quisserne D., Antonelli C. (2003) – Downstream grain-size distribution of superficial bed material and its hydro-geomorphological significance in a large and regulated river: the Rhône River in its delta area (France). *Géomorphologie : relief, processus, environnement*, 1, 33-50.

Blanc J.-J. (1977) – *Recherches de sédimentologie appliquée au littoral du delta du Rhône, de Fos au Grau-du-Roi.* CNEXO, 75/1193, 69 p.

Bravard J.-P. (1989) – La métamorphose des rivières des Alpes françaises à la fin du Moyen-Âge et à l'époque moderne. *Bulletin de la Société Géographique de Liège*, 25, 145-157.

Caillaud A., Boudet G., Gieulles D., Briand O. (1990) – Le littoral de Salin-de-Giraud (Commune d'Arles), évolution et programme de travaux de stabilisation. *Comptes rendus du Premier Symposium International de l'Association Européenne*, EUROCOAST, Marseille 9-13 juillet 1990, 729-733.

Carter R.W.G. (1988) – *Coastal Environments.* Academic Press, Londres, 617 p.

Crowell M., Leatherman S.P., Buckley M.K. (1991) – Historical shoreline change: error analysis and mapping accuracy. *Journal of Coastal Research*, 7 (3), 839-852.

Dolan R., Hayden B., Heywood J. (1978) – A new photogrammetric method for determining shoreline erosion. *Coastal Engineering*, 2, 21-39.

Duboul-Razavet C. (1956) – *Contribution à l'étude géologique et sédimentologique du delta du Rhône.* Mémoire de la Société Géologique de France, 76, 234 p.

Durand P. (1998) – Cinématique d'un littoral sableux à partir de photographies aériennes et de cartes topographiques. Exemple du littoral d'Argelès-Plage à Saint-Cyprien (Roussillon, France). *Géomorphologie : relief, processus, environnement*, 2, 155-166.

Durand P. (2000) – Approche méthodologique pour l'analyse de l'évolution des littoraux sableux par photo-interprétation. Exemple des plages situées entre les embouchures de l'Aude et de l'Hérault (Languedoc, France). *Photo-Interprétation*, 1/2, 3-17.

Galloway W.E. (1975) – Process framework for describing the morphologic and stratigraphic evolution of deltaïc depositional systems. *In* Brousard M. L. (Ed.) : *Deltas, models for exploration.* Houston Geology Society, 87-98.

Gautier E. (1994) – Interférences des facteurs anthropiques et naturels dans le processus d'incision sur une rivière alpine. L'exemple du Buëch, Alpes du Sud. *Revue de Géographie de Lyon*, 61 (1), 57-62.

Greslou M. (1984) – *Catalogue sédimentologique des côtes françaises. Côte de la Méditerranée de la frontière espagnole à la frontière italienne. Partie B : de Sète à Marseille.* Collection Direction des Études et Recherches d'EDF, Eyrolles, 106-187.

Institut Rhône Saône (IRS) (2001) – *Étude globale pour une stratégie de réduction des risques dus aux crues du Rhône. Étude du transport solide.* 1[ère] étape, rapport de synthèse, Institution interdépartementale des bassins Rhône-Saône, Valence, France, 5 vol., 469 p.

Jimenez J-A., Sanchez-Arcilla A., Bou J., Ortiz M.A. (1997) – Analysing short-term shoreline changes along the Ebro delta using aerial photographs. *Journal of Coastal Research*, 13 (4), 1256-1266.

Jorda M., Provansal M. (1996) – Impact de l'anthropisation et du climat sur le détritisme en France du sud-est (Alpes du Sud et Provence). *Bulletin de la Société Géologique de France*, 167 (1), 159-168.

Juniet F. (1962) – *Littoral de Camargue de la pointe de Beauduc au golfe de Fos. Évolution des profondeurs de 1959 à 1962 et orientation des études à venir.* Ponts et Chaussées, Service Maritime des Bouches -du-Rhône, 92 p.

Klingeman C., Bravard J.-P., Giuliani Y. (1994) – Les impacts morphodynamiques sur un cours d'eau soumis à un aménagement hydroélectrique à dérivation : le Rhône en Chautagne (France). *Revue de Géographie de Lyon*, 69 (1), 63-72.

Komar P.D. (1998) – *Beach Processes and Sedimentation.* 2[nd] ed., Prentice Hall, 544 p.

Kruit C. (1955) – Sediments of the Rhône delta. Grain size and Microfauna. *Verhandelingen van het Koninklijk Mijnbouwkundig Genootschap. Geologische serie* deel 15, 359-501.

Levoy F. (1989) – Morpho-cinématique et évolution récente prévisionnelle du rivage de Montmartin-sur-Mer. *Photo-Interprétation*, 1, 1-5.

L'Homer A. (1992) – Sea-level changes and impacts on the Rhône delta coastal lowlands. *In* Tooley M.J., Jelgersma S. (Eds.): *Impacts of sea-level rise on European coastal lowlands.* Blackwell, 136-152.

L'Homer A., Bazile F., Thommeret J., Thommeret Y. (1981) – Principales étapes de l'édification du delta du Rhône de 7000 BP à nos jours : variation du niveau marin. *OCEANIS*, 7 (4), 389-408.

Longé J.P. (1990) – Rehabilitation of "la flèche de la Gracieuse". *Comptes rendus du Premier Symposium International de l'Association Européenne*, EUROCOAST, Marseille 9-13 juillet 1990, 719-723.

May J.P., Tanner W. F. (1973) – The littoral drift power gradient and shorelines change. *In* Coates D. R. (Ed.): *Coastal Geomorphology*. University of New York, 43-60.

Miramont C., Guilbert X. (1997) – Variations historiques de la fréquence des crues et évolution de la morphogénèse fluviale en moyenne Durance (France, S-E). *Géomorphologie : relief, processus, environnement*, 4, 325-338.

Pardé M. (1925) – *Le régime du Rhône. Étude hydrologique*. Première partie, Étude générale. Institut des études rhodaniennes, université de Lyon. Masson, Paris, 883 p.

Paskoff R. (1994) – La cartographie prospective de l'évolution du trait de côte : un instrument indispensable pour l'aménagement des espaces littoraux. *Cahiers Nantais*, 41/42, 291-297.

Paskoff R. (1998) – La mer envahit la Petite Camargue, pourquoi ne pas la laisser faire ? *Pour la Science*, 247, p.16.

Paskoff R. (2001) – *L'élévation du niveau de la mer et les espaces côtiers*. Institut océanographique, Paris, 190 p.

Pichard G. (1995) – Les crues sur le bas Rhône de 1500 à nos jours. Pour une histoire hydro-climatique. *Méditerranée*, 3 (4), 105-116.

Picon B., Provansal M. (2002) – Faut-il se protéger de la mer ? Instabilités naturelles et politiques publiques dans le delta du Rhône. *Faire Savoirs*, Marseille, 2, 75-80.

Piégay H., Landon N., Bravard J.-P., Clément P., Liébault F. (1997) – Channel incision and potentiality of reversibility: the Drome river case, France. *Proceedings of the conference on management of landscapes disturbed by channel incision*, 20-22 May 1997, Oxford, Mississipi, USA, 53-59.

Pons A., Toni C., Triat-Laval H. (1979) – Édification de la Camargue et histoire holocène de sa végétation. *Terre et Vie, Revue d'Ecologie*, Marseille, suppl. 2, 13-30.

Pont D., Simonnet J.P., Walter A.V. (2002) – Medium-term changes in suspended sediment delivery to the ocean: consequences of catchment heterogeneity and river management (Rhône river, France). *Estuarine, Coastal and Shelf Science*, 54, 1-18.

Provansal M., Sabatier F. (2000) – Impact de la montée du niveau de la mer sur la côte du delta du Rhône. *In "Le changement climatique et les espaces côtiers. L'élévation du niveau de la mer : risques et réponses"*. Colloque proposé par la mission interministérielle de l'effet de serre, région PACA et DATAR, 12-14 octobre 2001, Arles, 78-81.

Provansal M., Vella C., Arnaud-Fassetta G., Sabatier F., Maillet G. (2003) – Role of sedimentary fluvial inputs in the mobility of the Rhône delta coast (France). *Géomorphologie : relief, processus, environnement*, 4, 271-282.

Robin M. (2002) – Télédétection et modélisation du trait de côte et de sa cinématique. *In* Baron-Yelles N. *et al.* (Ed.) : *Le littoral, regards, pratiques et savoirs*. Presses de l'École normale supérieure, Paris, 95-115.

Sabatier F. (2001) – *Fonctionnement et dynamiques morphosédimentaires du littoral du delta du Rhône*. Thèse de Doctorat, université d'Aix-Marseille III, 272 p.

Sabatier F., Provansal M. (2000) – Bilans morphologiques, répartition granulométrique et direction du transport sédimentaire autour du brise-lames de Ste Anne, delta du Rhône. *Génie Civil Génie Côtier*, Caen, 207-216.

Sabatier F., Provansal M. (2002) – La Camargue sera-t-elle submergée ? *La Recherche*, juillet-août 2002, 72-73.

Sabatier F., Raivard L. (2002) – Évolution bathymétrique de la pointe de l'Espiguette (delta du Rhône, mer Méditerranée) : résultats préliminaires. Actes du Colloque "*Espaces littoraux en mutation*", Commission Nationale de Géographie de la Mer, Dunkerque, 3-5 juin 2000, 101-105.

Shoshany M., Degani A. (1992) – Shoreline detection by digital image processing of aerial photography. *Journal of Coastal Research*, 8 (1), 29-34.

Sogreah (1995) – Étude de l'évolution du littoral sableux de la Camargue, 2 tomes, Grenoble.

Sogreah (1999) – *Aqueduc du Rhône à Barcelone, investigations supplémentaires. RMC8, Impacts sur les sédiments du Rhône*. Rapport 55 0470/JLR/R3 VA, Grenoble, 82 p.

Stapor F. W. (1974) – The "cell" concept in coastal geology. *In* Tanner W. F. (Ed.): *Sediment transport in the nearshore zone*. Florida State University, 1-11.

Suanez S. (1997) – *Dynamiques sédimentaires actuelles et récentes de la frange littorale orientale du delta du Rhône*. Thèse de doctorat, université de Provence, Aix-Marseille I, 283 p.

Suanez S., Bruzzi C. (1999) – Shoreline management and its implications for the coastal processes on the eastern part of the Rhône delta. *Journal of Coastal Conservation*, 5, 1-12.

Suanez S., Bruzzi C., Arnoux-Chiavassa S. (1998) – Données récentes sur l'évolution des fonds marins dans le secteur oriental du delta du Rhône (plage Napoléon et flèche de la Gracieuse). *Géomorphologie : relief, processus, environnement*, 4, 291-312.

Suanez S., Provansal M. (1996) – Morphosedimentary behaviour of the deltaïc fringe in comparison to the relative sea-level rise on the Rhône delta. *Quaternary Science Reviews*, 15, 811-818.

Suanez S., Provansal M. (1998) – Large scale evolution of the littoral of the Rhône delta (Southeast France). *Journal of Coastal Research*, 14 (2), 493-501.

Suanez S., Sabatier F. (1999) – Eléments de réflexion pour une gestion plus cohérente d'un système anthropisé : exemple du littoral du delta du Rhône. *Revue de Géographie de Lyon*, 74 (1), 7-25.

Suanez S., Simon B. (1997) – Utilisation de l'analyse diachronique dans l'étude de l'évolution du littoral du delta du Rhône (France, Sud-Est). *Photo-Interprétation*, 35, 3/4, 147-158.

Triat-Laval H. (1978) – *Contribution pollenanalytique à l'histoire tardi et postglaciaire de la végétation de la basse vallée du Rhône*. Thèse de l'université d'Aix-Marseille III, 344 p.

Vella C., Provansal M. (2000) – Relative sea-level rise and neotectonic events during the last 6,500 yr on the Southern eastern Rhône delta, France. *Marine Geology*, 170, 27-39.

Vella C. (2002) – Évolution paléogéographique du littoral de Fos et du delta du Rhône : implications archéologiques. *In* Rivet L. and Sciallano M. (Ed.) : *Vivre, produire et échanger : reflets méditerranéens*. M. Mergoil, Montagnac, 103-114.

Vernier E. (1976) – Édification et évolution de la flèche de Gracieuse (ouest du golfe de Fos). *Bulletin du B.R.G.M.*, Section IV, 2, 103-115.

Warner R.F. (2000) – Gross channel change along the Durance river, southern France, over the last 100 years using cartographic data. *Regulated river: research and management*, 16, 141-157.

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